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Investigations on Impact Testing of Head Injury Protection Helmets

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ABSTRACT

People are exposed to the risk of getting head injuries in various professional and sports activities like construction work, ice hockey, American football, motorcycle-, bicycle- and horse riding etc. The common interest of preventing brain damage during these activities has led to the development of corresponding different types of head protecting helmets. It has long been recognized that there is a need for quality control of such helmets with respect to how well they prevent head injury. Methods for testing helmets are usually based on translatory acceleration vector measurements on a headform-helmet assembly exposed to impact in a special drop test rig. However, there is reason to believe that rotational acceleration above a certain level would have detrimental effects on the brain just as severe as the effects of translatory acceleration. The disregard of rotation in present standards would therefore make helmet testing incomplete and may give users a false impression about helmet protection quality. Another problem is that accelerometers are rather difficult to calibrate, and often have considerable spread in output data. Specified repeatability and reproducibility may be hard to ensure and control within any particular testing laboratory. An even more difficult task is to obtain agreement between results from different laboratories for standard testing of helmets. A research study prompted by above problems, is reported here with results suggesting the use of improved methods to assertain more realistic and more reliable testing of protective helmets. It is intended that this study be followed up by evaluation of the suggested methods for production testing. Such efforts would be particularly justified from a consumers point of view.

BACKGROUND

People are exposed to the risk of getting head injuries in various professional and sports activities like construction work, ice hockey, American football, motorcycle-, bicycle- and horse riding etc. The common interest of preventing brain damage during these activities has led to the development of corresponding different types of head protecting helmets. It has long been recognized that there is a need for quality control of such helmets with respect to how well they prevent head injury. Methods for testing helmets are usually based on translatory acceleration vector measurements on a headform-helmet assembly exposed to impact in a special drop test rig. One important reason for using headform acceleration in these tests is to comply with available criteria on head injury severity. Such critera are usually derived from the well known Wayne State curve, which in turn is based on research on brain damage due to translatory acceleration of the human head. However, there is reason to believe that rotational acceleration above a certain level would have detrimental effects on the brain just as severe as the effects of translatory acceleration. The disregard of rotation in present standards would therefore make helmet testing incomplete and may give users a false impression about helmet protection quality.

Another problem is that accelerometers are rather difficult to calibrate, and often have considerable spread in output data. Specified repeatability and reproducibility may be hard to ensure and control within any particular testing laboratory. An even more difficult task is to obtain agreement between results from different laboratories for standard testing of helmets. A research study prompted by above problems, is reported here with results suggesting the use of improved methods to assertain more realistic and more reliable testing of protective helmets. It is intended that this study be followed up by evaluation of the suggested methods for production testing. Such efforts would be particularly justified from a consumers point of view.

EFFECTS OF IMPACT INDUCED ROTATION IN HELMET TESTING

Basic conditions of rotation

During impact tests on helmets it is unavoidable that the impact is more or less excentric. Depending on shape of the helmet and/or imperfect headform centering inside the helmet, the impact force may not go exactly through CG of the headform-helmet assembly and therefore may set up a corresponding rotational acceleration, more or less evident as tumbling of the tested helmet-headform. This condition will vary with different helmet design and also with different impact locations on any particular helmet. The result is that a certain part of the total drop energy is dissipated in terms of rotational energy, thereby causing the tumbling and a corresponding reduction in the recorded magnitude of translatory acceleration.

Evaluation and consequence of rotational energy

With helmet-headform mass (m), drop height (h) and impact velocity (v), the total dissipated drop energy (E) is obtained as

$$E = m\,g\,h = \frac{mv^2}{2} \qquad (1)$$

In terms of acceleration (a) integrated over the impact pulse duration time (t)

$$E = \frac{m}{2} \{ \int_0^\tau a \ dt \}^2 \qquad (2)$$

Under actual conditions with eccentric impact, the dissipation of this total energy (E) is divided on one translatory part (E_T) and one rotational part (E_r)

$$E = E_T + E_r \qquad (3)$$

With helmet-headform mass (m) and moment of inertia (I) this may be written in terms of corresponding accelerations (a), (a_T) and (a_r), integrated over the impact puls time (τ)

$$\frac{m}{2} \{ \int_0^\tau a_T \, dt \}^3 = \frac{m}{2} \{ \int_0^\tau a dt \}^2 - \frac{I}{2} \{ \int_0^\tau a_r \, dt \}^2 \qquad (4)$$

During impact, part of the original drop energy is transformed from translatory to rotational energy. This would mean a corresponding lower level pulse of the measured translatory acceleration (a_T).

In a preliminary deduction (Appendix A) it is found that of the dissipated total impact energy (E), the rotational part (E_r) increases with the square of the moment arm length (R) as indicated in Figure 1.

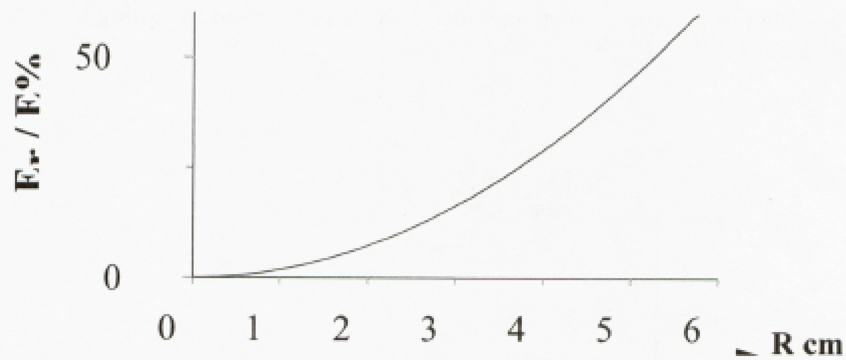


Figure Variation of Rotational Energy With Eccenter Moment Arm

Therefore under actual conditions with eccentric impact and the resulting tumbling, only half of the total drop energy may be accounted for during certain types of tests and with certain designs of helmet. This would be true particularly for side blows and for helmets with protuding ridges and would hint the incompleteness of present helmet testing from a medical point of view as well as for certification requirements. Since there is no way of accounting for rotational energy in presently used impact tests on helmets, it follows that this testing standard may be unfair in judging the protection quality of these certain helmets. For similar reasons different testing methods, like guided vs unguided drop impact tests, may also give different undue bias to the results. This may in fact lead the market to shape helmets so as to make them easier pass impact tests by dissipating a larger portion of the total energy in the form of rotation, resulting in a false impression about helmet protection safety.

ON THE USE OF FORCE INSTEAD OF ACCELERATION FOR HELMET TESTING

Simulation of the helmet impact testing process

Mathematical model. In order to investigate the basic relation between acceleration and corresponding forces arising in the helmet impact testing process, a simplified mathematical model was established. The simulated system consists of a nonlinear spring-mass-damper model with three degrees of freedom. Corresponding nonlinear differential equations of motion were solved by computer and the Runge Kutta method. This simulated system so far includes only straight impact without rotation, but has the potential of also taking in eccentric impact with rotation.

Results of computer simulation. Output data simulating drop tests with a free falling head were obtained with various input parameters. The results indicate by the examples of Figures 2 and 3 a fairly linear relation between the characteristics of anvil force (P) on the outside surface of the helmet and headform acceleration (a). This would be particularly true if the comparison is made between such data obtained as integrated averages over the entire impact pulse duration. Based on the computer results the following relation between headform impact acceleration (a) and helmet impact force (P) may be assumed

$$a = q \ P / m \tag{5}$$

where (q) is a constant or a transfer function, which may be determined by testing or by using already available test data.

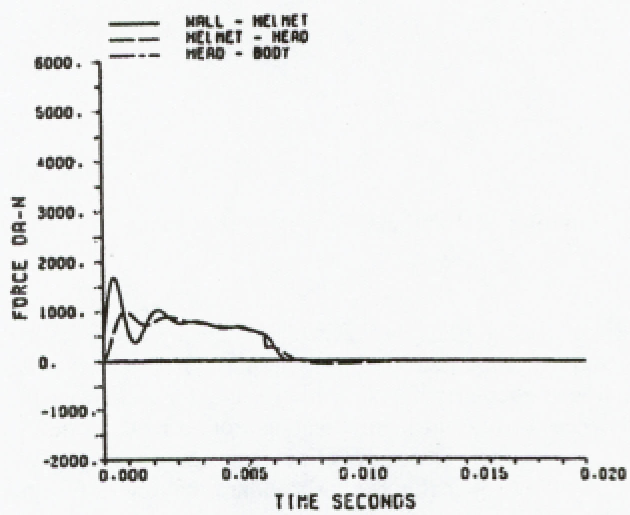


Figure 2: Helmet Drop Test Simulation: Falling head 5kg, Force characteristics

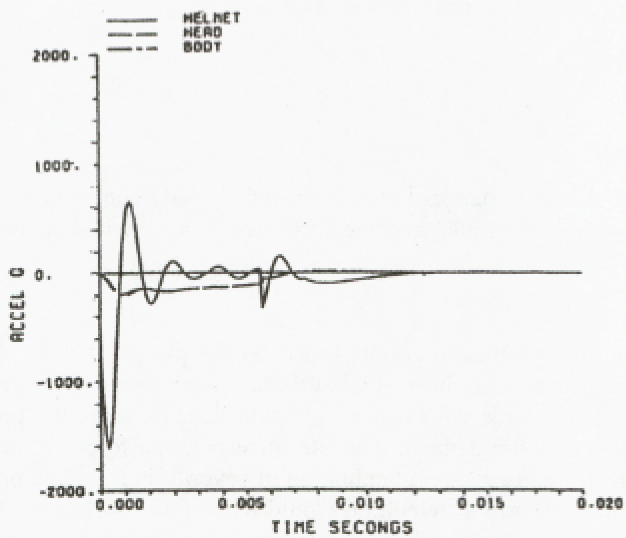


Figure 3: Helmet Drop Test Simulation: Falling head 5kg, Acceleration characteristics

Suggested application

In consequence with results obtained by the simulated impact, a reasonable assumption would be that it is possible to base brain damage severity in helmet testing on measured helmet-anvil contact force, rather than on the presently used headform acceleration. This would eliminate the special difficulties with acceleration measurements and facilitate the helmet testing procedure, including calibration, with consequences of better accuracy and better possibilities of agreement between results from different testing laboratories. It is therefore suggested that measured helmet contact force pulse data are converted to headform acceleration to suit computation of severity index as follows.

With measured value of momentary helmet-anvil contact force (P) and headform mass (m) the approximated headform acceleration (a) is obtained by the previously assumed relation in (5).

Severity index (GSI) may then be computed as the time integral over impact pulse duration (τ)

$$GSI = \int_0^{\tau} a^{2.5}\, dt \qquad (6)$$

Maximum headform acceleration (a_{max}) is usually registered as a complement to (GSI) . Using the assumed relation between force (P) and acceleration (a)

$$a_{max} = q \; P_{max} / m \qquad (7)$$

The pulse characteristic of force (P) as well as acceleration (a) is usually sharply pointed and therefore its recorded value is to a large degree depending on the variability of filters used in the collection of the raw data. To avoid this uncertainty in the judgement of helmet protection quality, it should considered to base helmet quality rating on the integrated time average (P_{ave})of the force pulse instead of the customary maximum headform acceleration (a_{max})

$$P_{ave} = 1 / \tau \left\{ \int_0^\tau P \, dt \right\} \qquad (8)$$

Instead of the present standard condition of a maximum limit on recorded headform acceleration, a corresponding integrated average acceleration (a_{ave}) could be used.

$$a_{ave} = q \; P_{ave} \,/\, m$$

which would avoid the uncertainties of results based on sharply pointed acceleration characteristics. Results of helmet testing using the above method based on recorded force rather than acceleration, would be on the conservative side with respect to brain damage since the presently used headform acceleration characteristic is more damped than the corresponding force on the outside shell and also since helmet mass is neglected in above computation of severity index. The phase difference existing between anvil force and headform acceleration would have minor influence on severity index (GSI) and the average pulse force (P_{ave}) because of the integration involved in the computations.

IMPACT FORCE TRANSDUCER

A special six component transducer has been designed as a research tool for anvil impact force tests on protective helmets.The transducer design is based on previous experience with multicomponent balances for wind tunnel testing work. The transducer is located on top of the anvil and has therefore the advantage of being stationary, which simplifies the instrumentation compared with the travelling triaxial accelerometer used in present standard.

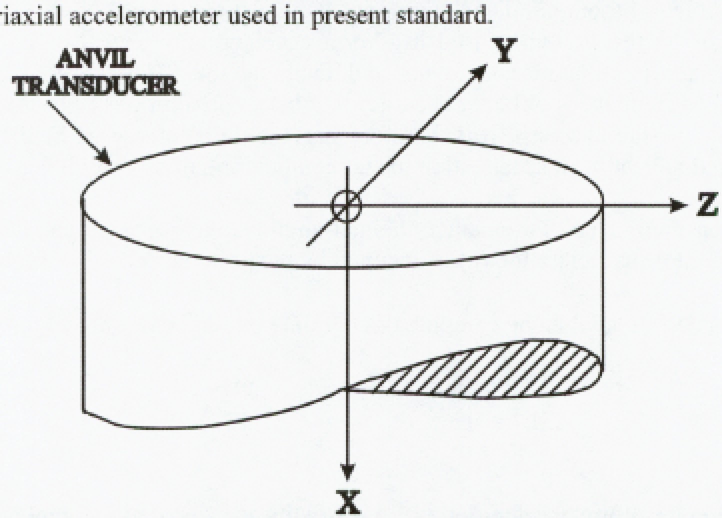


Figure 4: Transducer Fixed coordinate system for forces and moments

The force and moment components are referred to a given transducer fixed coordinate system as shown in figure 4 and with the following designations

- Forces (P_X, P_Y, P_Z)
- Moments (M_X, M_Y, M_Z)

Transducer signals would give complete information about the impact force and moment vectors to magnitude and direction in space. A desired natural frequency of at least 1 kHz is possible to attain with this design, but would depend on the coupling between transducer and helmet-headform masses as well as on the nonlinearities involved.

Knowing the force components (P) and corresponding moments (M) it is possible to compute translatory and rotational energy imparted on the helmet-headform assembly during impact.

CONCLUSIONS

Rotational energy in helmet testing

Present day impact testing standard for head protection helmets is rather incomplete, since it disregards any rotational portion ot the totally dissipated drop energy. Only the translatory part of impact acceleration is considered when judging protection quality, which may lead to unfair certification of helmets. With the medical background of impact rotational violence as a probable cause of most brain injuries, it would seem desirable to evalulate a proposed method of testing protective helmets including the combined effects of both translatory and rotational violence.

Helmet testing based on impact force rather than acceleration

In general, standard test criteria on protective helmets are presently based on impact acceleration measurements. These measurements are difficult with regard to such factors as calibration, reproducibility and compatibility between different testing laboratories. Work with computer simulation of impact testing has indicated a possibility to measure impact force instead of acceleration as a basis for test severity. Application of impact force measurments would have several advantages like:

- Stationary anvil force transducer makes testing equipment simpler and easier to handle than present standard with a travelling accelerometer in the dropped headform
- Shorter tracing chain to unit normals
- Simple, more accurate calibration by deadweights
- Allows frequent intermediate checking on accuracy by direct calibration (no MEP pad) on production site
- Would make it easier for different testing laboratories to produce comparable results
- Should make it possible to consider rotation in helmet testing.

It is intended to follow up this study by a practical testing project using the suggested anvil transducer for verification.

REFERENCE

Johnson, G.I. Development of an Impact Testing Method for Protective Helmets. "Safety in Ice Hockey", ASTM STP 1050, pp. 240-261,1989.

APPENDIX A

G. I. Johnson, March 1992, CEN/TC 158WG 7 N 22

Share of rotational energy in impact testing of protective helmets

A theoretical investigation under simplified assumptions.

1) Computation of moment of inertia for headform including helmet

Headform with helmet is assumed to have spherical shape

$$I_{SOLID} = \frac{2}{5} W R^2 , \qquad I_{SHELL} = \frac{2}{3} W R^2$$

For thick shelled headform

$$I = \frac{1}{2} W R^2$$

with $\quad W = 5 \text{ kg}; \quad R = 0.09 \text{ m}$

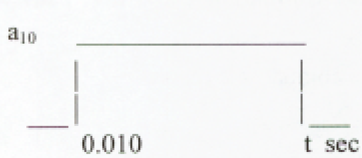
is $\quad I = \frac{1}{2} \cdot 5 \cdot 0.09^2 = 0.0202 \text{ kgm}^2$

2) Force during impact compression

With drop height 1 m the velocity (v) is

$$v = \sqrt{2 g h} = \sqrt{2 \cdot 9.91 \cdot 1} = 4.5 \text{ m/s}$$

Acceleration under constant retardation during 10 millisec



$$a_{10} = \frac{4.5\text{-}0}{0.010} = 450 \text{ m/s}^2$$

$$= 45 \text{ g}$$

With retardation time 1 millisec $\quad a_1 = 450$ g

Consider a realistic retardation time of 2 millisec
with corresponding acceleration $\quad a_2 = 225$ g

Say $\quad a = 200$ g

Then the force (P) is $P = a \cdot W = 200 \cdot 5 \cdot 9.81 = 10000$ N

3) Find corresponding rotational acceleration

Assume eccentric impact with moment arm $r = 10$ mm (0.01 m).

Corresponding moment

$$M = P \cdot r = 10000 \cdot 0.01 = 100 \text{ Nm}$$

Rotational acceleration (a_r)

$$M = a_r \cdot I$$

$$a_r = \frac{M}{I}$$

$$= \frac{100}{0.0202} = 5000 \text{ rad/s}^2$$

Achieved angular velocity (ω) after $t = 2$ millisec

$$\omega = a_r \cdot t$$

$$= 5000 \cdot 0.002$$

$$= 10 \text{ rad/s}$$

Rotational energy (E_r)

$$E_r = \frac{I\,\omega^2}{2}$$

$$= \frac{0.0202 * 10^2}{2}$$

$$= 1 \text{ Nm}$$

4) Ratio (F) between rotational energy (E_r) and total drop energy (E_T)

Total energy (E_T)

$$E_T = \frac{Wv^2}{2}$$

$$= \frac{5*4.5^2}{2}$$

$$= 50 \text{ Nm}$$

$$F = \frac{E_r}{E_T} = \frac{WR}{2}\frac{1}{2}\left(\left(\frac{P.r.t}{\frac{WR^2}{2}}\right)^2 / \frac{Wv^2}{2}\right) = \frac{2P^2 r^2 t^2}{W^2 R^2 v^2}$$

$$= \frac{1}{50} = 0.02 = 2\,\%$$

Check of compression (S) under the impact force (P)

$$E_T = S \,.\, P$$

$$S = \frac{E_T}{P}$$

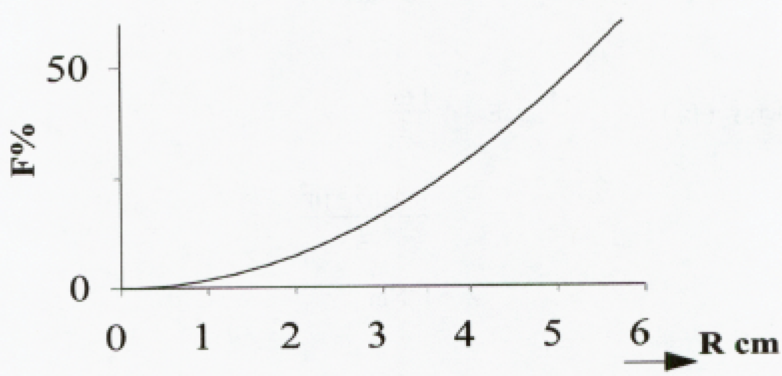
$$= \frac{50}{10000}$$

$$= 0.005 \text{ m}$$

Conclusion

The share of rotational energy in the total drop energy increases with the square of the length of moment arm for eccentric impact.

This is illustrated by the following diagram



In a similar way the share of rotational energy also increases with the squares of impact force and pulse duration but decreases with the squares of the headform mass, headform diameter and impact velocity according to

$$F = \frac{2P^2 r^2 t^2}{W^2 R^2 v^2}$$